LCA Methodology and Case Study

Life Cycle Energy Assessment of Alternative Water Supply Systems

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Abstract

Goal, Scope and Background. This paper discusses the merging of methodological aspects of two known methods into a hybrid form applied to water supply systems. Water shortages are imminent due to scarce supply and increasing demand in many parts of the world. In California, this is caused primarily by population growth. As readily available water is depleted, alternatives that may have larger energy and resource requirements and, therefore, environmental impacts must be considered. In order to develop a more environmentally responsible and sustainable water supply system, these environmental implications should be incorporated into planning decisions.

Methods. Comprehensive accounting for environmental effects requires Life Cycle Assessment (LCA), a systematic account of resource use and environmental emissions caused by extracting raw materials, manufacturing, constructing, operating, maintaining, and decommissioning the water infrastructure. In this study, a hybrid LCA approach, combining elements of process-based and economic input-output-based LCA was used to compare three supply alternatives: importing, recycling, and desalinating water. For all three options, energy use and air emissions associated with energy generation, vehicle and equipment operation, and material production were quantified for life-cycle phases and water supply functions (supply, treatment, and distribution). The Water-Energy Sustainability Tool was developed to inform water planning decisions. It was used to evaluate the systems of a Northern and a Southern California water utility.

Results and Discussion. The results showed that for the two case study utilities desalination had 2–5 times larger energy demand and caused 2–18 times more emissions than importation or recycling, due primarily to the energy-intensity of the treatment process. The operation life-cycle phase created the most energy consumption with 56% to 90% for all sources and case studies. For each water source, a different life-cycle phase dominated energy consumption. For imported water, supply contributed 56% and 86% of the results for each case study; for desalination, treatment accounted for approximately 85%; for recycled water, distribution dominated with 61% and 74% of energy use. The study calculated external costs of air pollution from all three water supply systems. These costs are borne by society, but not paid by producers. The external costs were found to be 6% of desalinated water production costs for both case studies, 8% of imported water production costs in Southern California, and 1–2% for the recycled water systems and for the Northern California utility's imported water system.

Conclusion. Recycling water was found to be more energy intensive in Northern than in Southern California, but the results for imported water were similar. While the energy demand of water recycling was found to be larger than importation in Northern California, the two alternatives were competitive in Southern California. For all alternatives in both case studies, the energy consumed by system operation dominated the results, but maintenance was also found to be significant. Energy production was found to be the largest contributor in all water provision systems, followed by materials production. The assessment of external costs revealed that the environmental effects of energy and air emissions caused by infrastructure is measurable, and in some cases, significant relative to the economic cost of water.

Recommendation and Perspective. This paper advocates the necessity of LCA in water planning, and discusses the applicability of the described model to water utilities.

Keywords: Decision support; desalination; hybrid approaches; life cycle energy assessment; recycled water; water reuse; water supply

Introduction

This paper discusses the merging of methodological aspects of two known methods into a hybrid form applied to water supply systems.

Growing water demand and shrinking water supply are driving the need for new water sources in many parts of the world. Rapid population growth, especially where little rain falls, will dramatically increase water demand. For example, California is expected to experience a significant shortage by 2010 without changes to the existing water provision system. Over six trillion liters of water are provided for urban use each year in the state. A report from the U.S. Department of Interior indicates that a water supply crisis is somewhat or highly likely for many urban coastal areas of California [1]. To prevent such a crisis, the California Urban Water Management Plan (UWMP) Act requires water utilities to plan their water supply sources for 20 years in the future [2]. The water utilities are required to submit their next 20-year plans in 2005. Three different water supply sources are frequently considered for future water supply by California utilities as well as in many coastal areas of the world: importing, desalinating, and recycling water. The U.S. government is encouraging development of desalinated water supply to meet demand despite the energy-intensity of this alternative [1]. The decisions made for each utility's

UWMP planning process will create systems which will have a service life of decades. Unfortunately, the comprehensive environmental effects of these systems are typically not known, rendering fully informed decision-making impossible.

To promote more sustainable water supply planning decisions, the authors created a model which quantifies material and energy inputs into water systems as well as environmental outputs. The model has been implemented in a computer-based decision-support tool, the Water-Energy Sustainabilty Tool (WEST), which assesses environmental effects of water utilities considering or currently using these water alternatives. The tool can be used by individual utilities, state-wide planners, and policy-makers to evaluate the environmental effects of their water supply decisions and incorporate those into the planning process [3].

Some environmental effects are not currently quantified by WEST. For instance, emissions to land and water are not considered. In addition, ecological effects are not included. These include the effects of brine disposal from desalination and the effects of withdrawing water from the source on downstream habitat and water quality as well as other environmental effects. These effects may be quantified in future versions of WEST.

A strong connection exists between water provision and energy consumption. Worldwide, 2–3% of energy consumption is used to pump and treat urban water [4]. In the U.S., approximately 75 billion megawatt-hours, 3% of national electricity consumption, was consumed for water and wastewater services. In the next 20 years, energy requirements for these services are expected to grow by 33%. As readily-available water sources are depleted, future supply options will likely have higher energy requirements.

In addition, resource consumption and construction processes will increase the negative environmental burden. One German study estimated that urban infrastructure, including roads and water, sewer, and district heating pipelines account for 10–20% of the total urban building mass; the value varies inversely with building density [5]. Because the infrastructure in this country is aging, the U.S. Environmental Protection Agency (EPA) has estimated that nationwide capital spending to provide drinking water would have to be $154–446 billion between 2000 and 2019 [6]. The materials used and the construction processes needed to install this infrastructure will increase the life-cycle environmental effects of these systems.

Increasingly, society is concerned about sustainability, including the effects of water systems. Recent publications described the sustainability of recycled water systems [7] and the environmental effects of water and wastewater systems in Sydney, Australia [8]. In addition, a pair of articles presented an assessment of water supply choices in Spain [9,10]. The first article assesses desalination technologies and determines that without energy recovery, reverse osmosis (RO) is the preferable technology. When energy recovery is included, the alternatives are similar. The second article compares desalination using RO to importing water from the Ebro River. The study concluded that, given the current state of desalination technology, water transfers are preferable. However, RO membrane efficiency improvements and electricity generation emission reductions in the future could alter the outcome. Furthermore, California's Santa Clara Valley Water District, along with other Silicon Valley industries, announced plans to reduce greenhouse gas emissions by 20% below the 1990 level by 2010 [11]. The information provided by WEST will inform the selection of more sustainable choices.

Several prior studies have been conducted which inform the current research, including analyses of European and Australian water systems [8,12,13], as well as more focused analyses of water filtration alternatives [14], distribution infrastructure [5,15], recycling plant energy use [16], and disinfection practices [17].

1 Approach and Method

WEST uses Life Cycle Assessment (LCA), a systematic, quantitative approach to evaluating the impacts of a product or process from 'cradle' to 'grave.' It considers all energy and environmental implications of processes through the entire life-cycle, including design, planning, material extraction and production, manufacturing or construction, use, maintenance, and end-of-life fate of products (reuse, recycling, incineration, or landfilling) [18]. LCA targets resource use and environmental impact reduction efforts and allows water agencies to properly plan their water supply choices.

LCA currently relies on two major approaches: process-based LCA and economic input-output analysis-based LCA (EIO-LCA) [19]. The process-based LCA methodology has been defined by the Society of Environmental Toxicology and Chemistry (SETAC) [20,21], the EPA [22], and the International Organization for Standardization (ISO) 14040 series standards [23–25], and involves four main steps: goal and scope definition, inventory analysis, impact analysis, and improvement analysis [26]. The basis for inventory modeling and data collection is a series of (typically man-made) processes for all the life-cycle stages of involved products and services. LCA is an iterative process, so an interpretation of the results occurs after each step. Impact analysis attempts to determine the impacts of emissions and wastes on humans and our environment (e.g., global warming potential and human toxicity potential).

EIO-LCA is a matrix-based LCA approach [27] that utilizes the U.S. economy's input-output tables as a general interdependency model that maps comprehensively the interactions between all sectors of the economy, and identifies product and service supply chains. Economic data are combined with resource consumption and environmental emission and waste data (e.g., energy use, toxic air emissions, hazardous waste). For a producer's expenditure in a given economic sector, the model estimates how much is spent directly in that sector, as well as in the supply chain, and calculates corresponding environmental emissions and wastes associated with the specified expenditures. EIO-LCA has been applied to a number of products and services (e.g., [28,29]).

To allow for most detailed and comprehensive analyses, WEST utilizes a hybrid LCA approach, incorporating ele-

ments from both process-based LCA and EIO-LCA. Generally, WEST relies on EIO-LCA to determine the effects of material acquisition, transformation and production. EIO-LCA provides results for the entire material production supply chain while minimizing time and data requirements necessary for the analysis. Process-based LCA is used to assess the environmental effects of system construction and operation to obtain process-specific results. This hybrid approach combines the best of process-based LCA and EIO-LCA while minimizing or eliminating the disadvantages of each.

2 Description of the WEST Decision-Support Tool

WEST is an MS-Excel-based decision-support tool that considers the materials provision, construction, operation, and maintenance phases of the life-cycle of water supply systems. Currently, the end-of-life phase is not included because prior studies have found it not to be a significant contributor to the overall environmental burden (one study quantified it as less than 1% [14]), but corresponding effects will be added in the future.

Models have been developed to compare imported, desalinated, and recycled water. Importation and desalination provide potable water, while recycled water is a non-potable source generally used for irrigation and commercial or industrial applications. However, all three water sources are compared on an equal basis by water planners because each unit volume of recycled water offsets water needed for potable use, and two-thirds of urban water consumption is in non-potable applications [30].

Emissions from four major activities are included in the tool: production of all material inputs into the system, material delivery by truck, ship, train or urgent overnight delivery by airplane, equipment use for construction or maintenance activities, and production of electricity and fuels used in the system. The structure of WEST, including the data which must be entered into the tool by the user, is illustrated in **Fig. 1**.

A functional unit of 123 million liters of water delivered to the customer was selected as the basis of comparison for the alternatives as it represents the approximate size of the smallest water supply component of typical systems (including one of the case studies presented herein). The functional unit is equivalent to 100 acre-feet; an acre-foot is a unit of volume used in water supply planning in the U.S. A time horizon of 100 years was selected because of the expected life of major water supply components, such as dams and treatment plants. Materials with shorter service lives (e.g., pumps, filters, and valves) are assumed to be replaced each time their service life expires until the 100-year time horizon is achieved.

The construction phase includes emissions due to material production for the initial construction and installation, operation of construction equipment and delivery vehicles, and production of electricity and fuel. Emissions from the construction phase were allocated proportionally to the unit volume of water delivered to the customer given the time frame of the analysis. The operation phase includes production and delivery of routinely used non-capital materials (e.g., water treatment chemicals and bag filters), sludge disposal, and electricity and fuel production. The maintenance phase includes production and delivery of capital materials used to maintain the system (e.g., replacement pumps, valves, and reverse osmosis membranes), emissions from maintenance vehicles, and electricity and fuel production.

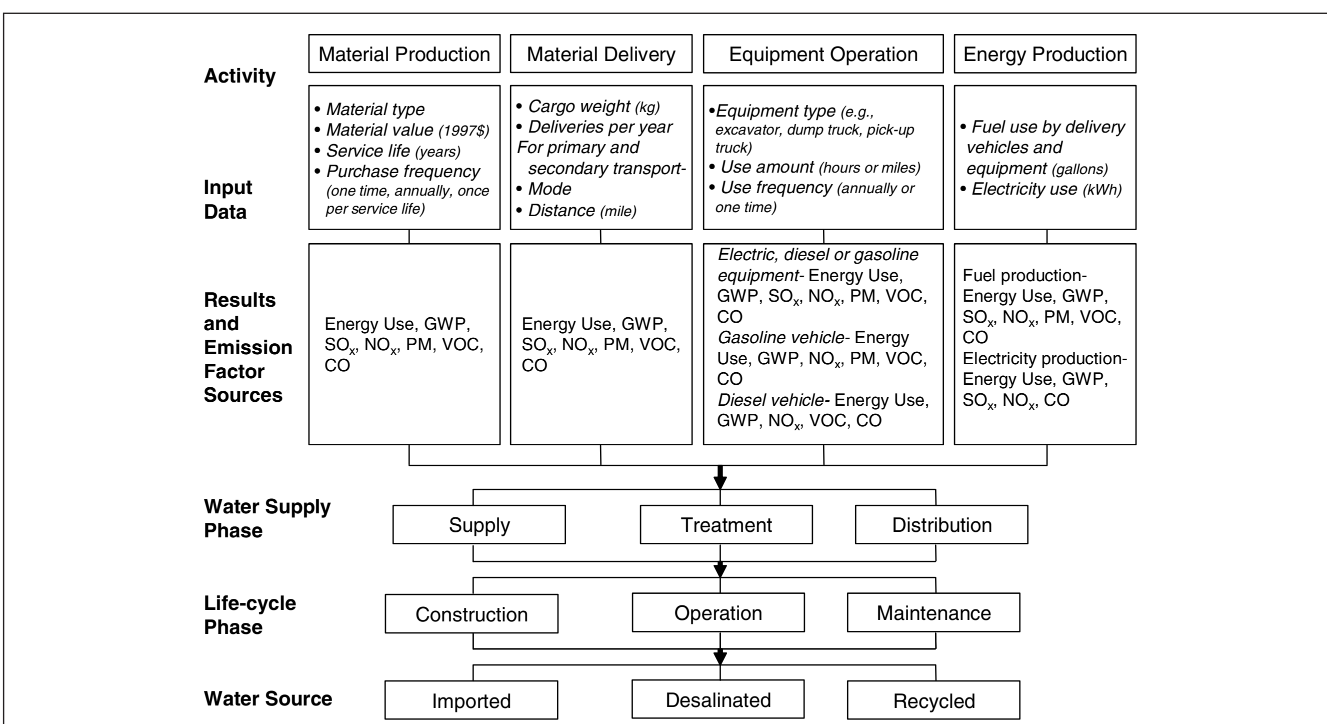


Fig. 1: The Structure of WEST

Emissions were assigned to three water supply phases: supply, treatment, and distribution. In most cases, the water supply phase begins at the water source and includes the infrastructure necessary to provide raw water to the treatment plant. The treatment phase includes all activities which occur at the treatment plant. Distribution consists of all infrastructure needed to deliver treated water to customers (e.g., pipelines and pump stations).

Currently, WEST can assess energy consumption as well as the emissions of greenhouse gases and the resulting global warming potential (GWP), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOC), and carbon monoxide (CO). Energy use and emission factors for each pollutant and phase were calculated. An example calculation for emissions of NO_x from the tailpipe of a dump truck (model year: 2002) used to transport sludge routinely from a treatment plant to a landfill located 50 km away (100 km roundtrip) is given in **Eq. 1**. The values are normalized to the functional unit of 123 million liters using the annual water production of 10 billion liters for the treatment plant.

$$\frac{6.49 gNO_x}{mile} * \frac{0.62 mile}{km} * \frac{100 km}{trip} * \frac{500 trips}{year} * \frac{year}{10 * 10^9 L} * \frac{123 * 10^6 L}{functionalunit} = \frac{2575 gNO_x}{functionalunit} \quad (1)$$

The results were translated into monetary terms using estimates of external costs of air emissions [31]. By monetizing the results, different emissions can be compared on an equivalent basis. In the original study, external costs are reported in 1992 dollars. The values were converted to 1997 dollars using a 2% discount rate. An example conversion to external costs for the NO_x emissions calculated above is shown in **Eq. 2**.

$$\frac{2575 gNOx}{functionalunit} * \frac{\$0.00117}{gNO_x} = \frac{\$2.89}{functionalunit} \quad (2)$$

3 Case Studies

Two California water systems have been analyzed using WEST. One utility, the Marin Municipal Water District (MMWD) is located in Marin County in Northern California. The other, the Oceanside Water Department (OWD) is in San Diego County in Southern California. Both utilities serve a population of approximately 200,000 people and provide a total of approximately 40 billion liters of water each year. However, the climate in the two areas differs. Marin County receives 762 mm of rainfall annually while Oceanside receives only 254 mm. **Table 1** provides additional detail on the case study systems.

The information used in the analyses was obtained from a combination of published information from each utility (e.g., [32–38]), site visits, and industry information (e.g., [39–43]). In both systems, some imported water infrastructure is used to supply water to other utilities. In these cases, construction and maintenance emissions are allocated to the case study utilities based on their average annual water provision through the shared infrastructure. Some system components not specified in Table 1 were also analyzed (e.g., instrumentation, controls, electrical equipment, and piping in treatment plants).

The MMWD currently obtains most of its water from rainfall (72%); this water is not included in the analysis. The remaining water is supplied by importation (26%) and recycling (2%). The imported water is obtained from a pristine source approximately 32 km away, and is pumped over hilly terrain to the MMWD service area. The water is disinfected and then pumped through a distribution system to the customer. Due to the quality of the water source, no other treatment is needed. The recycled water is taken from the effluent of a wastewater treatment plant located in the service area, filtered, disinfected, and provided to customers. The water is not potable and is used for irrigation, commercial car washes, and similar purposes.

Due to reliability and environmental concerns, the MMWD is considering replacing imported water with desalinated water. The desalination system, as planned, would draw water from the San Francisco Bay and treat it through a reverse osmosis process. The treated water would then be distributed using the existing potable water distribution system; however, additional pipelines, storage tanks, and pump stations would be constructed to connect the desalination plant to the existing system.

The OWD imports 92% of its water from the Colorado River and the Sacramento-San Joaquin River Delta, sources located hundreds of miles from the service area. Before being delivered to the consumer, water is treated by a conventional treatment process which typically includes coagulation, flocculation, filtration, and disinfection. The utility provides almost 8% of its water supply by using an RO process to desalinate brackish groundwater. The remaining water (less than 1% of total water production) comes from a recycled water plant which filters effluent from a wastewater treatment plant. Recycled water is sold to provide water for irrigation.

4 Results

Table 2 shows emission and energy use factors for all life-cycle and water supply phases for both case studies. The emission factors for the desalination system are the largest for all analyzed substances. In both cases, VOC emissions from desalination systems are over 14 times larger than from the imported water systems and 16 to 18 times larger than from the recycled water systems. The increased VOC emissions are due mainly to the production of RO membranes. For the other substances, desalination produces 2 to 7 times more emissions than the other alternatives.

Energy use is the largest for the desalination systems, particularly in the operation life-cycle phase and the treatment water supply phase, primarily on the account of the RO systems in place. Producing desalinated water in the MMWD

Table 1: Summary of the infrastructure for the case studies

	Electricity[a] (kWh/year)	Chemicals[a] (tonnes/year)	Buildings (total m^2)	Pipelines[b] (km)	Fittings (number)	Valves (number)	Valve boxes (number)	Pumps (number)	Pump stations (number)	Tanks (number)	Treatment processes	Significant additional facilities
Marin Municipal Water District[c]												
Imported Water – 10.0 billion liters												
Supply[d]	9770			56	152	19	15	10	8	4		6 intake wells
Treatment	25	136	9.3					4		3	Disinfection	
Distribution	22100			1400	8534	60000	30000	195	98	132		
Desalinated Water – 10.0 billion liters												
Supply	3795			3.2	9	5	1	6	1			Intake pier
Treatment	38460	1220	460	1.6	10	1		14		8	Flocculation, filtration, reverse osmosis, disinfection	
Distribution[e]	2,220			21	52	17	11	12	3	4		
Recycled Water – 863 million liters												
Supply	390			1.6	4	2		1				
Treatment	165	36.9	46					9		4	Coagulation, filtration, disinfection	
Distribution	1325			40	251	32	31	10	4	5		
Oceanside Water Department												
Imported Water – 37.3 billion liters												
Supply[d]	76090			1300		3		285	14	1		13 dams
Treatment[d]	800	7620	2800					42		13	Flocculation, filtration, disinfection	
Distribution[f]	648			880	4905	8943	4400	23	9	12		
Desalinated Water[f] – 3.58 billion liters												
Supply	680			4.8		10		6	1			8 wells
Treatment	7140	360.7	510					6	10	5	Filtration, reverse osmosis, disinfection	
Recycled Water – 98.7 million liters												
Supply	25				4	2		1				
Treatment	5		37								Filtration	
Distribution	130			3.2	21	6	4	1				

Notes:

[a] Electricity and chemical results include only consumption by the case study utility; electricity and chemicals used by shared facilties to produce water for other utilities are not included.

[b] For the supply systems, the pipeline category includes canals, tunnels, conduits, and pipelines; for distribution systems, the category consists of underground pipe.

[c] The volume of water presented does not include water obtained from reservoirs in the service area (72% of MMWD's water supply). Desalinated water is being considered as a replacement for the current imported water supply; water from these two sources would not be provided concurrently.

[d] Some facilities in this category process water for other utilities; results in this section are allocated proportionally based on water provision.

[e] These results include additional facilities necessary to upgrade the potable distribution system for desalinated water. The existing potable distribution system (shown in this table as imported water results) will be used to transport desalinated water as well.

[f] Imported and desalinated water are distributed using the same distribution system; results are allocated to these systems based on the volume of water produced by each.

system uses three times more energy than recycled water and five times more than imported water. The OWD desalination system uses one-half of the energy and emits about one-half of the emissions of the MMWD but is still twice as energy-intensive as importing or recycling water. The difference is due to the salinity of the utilities' salt water sources. Marin County plans to process water from the San Francisco Bay. The assumed influent total dissolved solids (TDS) concentration is 32,000 mg/l; the actual TDS varies seasonally and may be as low as 10,000 mg/l. The brackish groundwater used by the OWD consistently has a TDS of approximately 1,500 mg/l. More energy is required to remove the additional salt from the higher salinity water. In addition, membranes and other process equipment must be replaced more often when treating higher salinity water. Recycling water is more energy intensive in the MMWD system than in the OWD, but the results for imported water are similar.

The energy consumption associated with the distribution systems is significantly different for the two utilities. The

Table 2: Emission factors for water supply systems

Emission Factors (Mg/functional unit)						
	Import		Desalinate		Recycle	
	MMWD	**OWD**	**MMWD**	**OWD**	**MMWD**	**OWD**
GWP	60	75	290	145	112	67
SOx	0.10	0.05	0.58	0.25	0.08	0.04
NOx	0.11	0.10	0.61	0.28	0.14	0.08
PM	0.02	0.01	0.09	0.04	0.02	0.01
VOC	0.02	0.01	0.28	0.12	0.02	0.01
CO	0.16	0.10	0.53	0.23	0.13	0.08
Energy Use Factors by Life-cycle Phase (GJ/functional unit)						
Construction	73	40	163	82	65	38
Operation	508	840	2192	1249	1022	765
Maintenance	207	62	1528	640	130	48
Energy Use Factors by Water Supply Phase (GJ/functional unit)						
Supply	442	811	186	127	205	122
Treatment	12	29	3247	1742	259	100
Distribution	334	102	450	102	753	629
GWP Factors by Life-cycle Phase for Supply System (Mg CO_2 eq./functional unit/pipe mile)						
Construction	0.02	0.01	0.33	0.13	0.21	1.6
Operation	2.4	5.1	6.8	3.0	34	95
Maintenance	0.01	0.003	0.32	0.17	0.41	5.5
GWP Factors by Life-cycle Phase for Distribution System (Mg CO_2 eq./functional unit/pipe mile)						
Construction	0.02	0.005	0.02	0.005	0.13	0.75
Operation	0.02	0.001	0.05	0.001	2.17	23
Maintenance	0.07	0.01	0.06	0.01	0.07	0.84

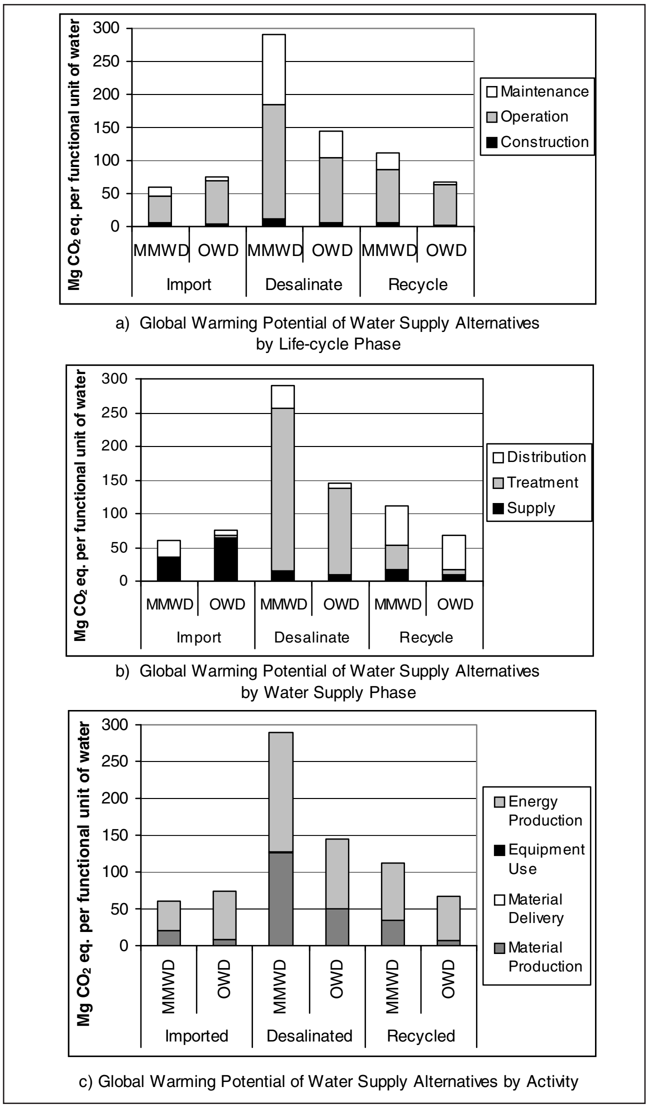
Note: The functional unit is equivalent to 123 million liters.

OWD distribution system is designed so most water is distributed by gravity, whereas the MMWD must rely on significant pumping. Furthermore, the MMWD system requires additional construction to connect the desalination plant to the existing distribution system while the OWD system uses only the existing infrastructure. Both factors contribute to the MMWD's higher energy use in the distribution phase.

In addition, Table 2 shows GWP normalized by length of supply aqueducts and distribution pipelines for comparison. Though operation phase results vary directly with the volume of water processed, the emission factors for the construction and maintenance phases should reveal how the systems are affected by economies of scale. For instance, construction and maintenance for the imported water supply systems of both utilities have lower emission factors than the corresponding factors for the smaller desalinated and recycled water supply systems. The emission factors for construction and operation of the distribution portion of the recycled water systems are larger than for imported and desalinated water: the separate distribution system for recycled water is used only for non-potable water and therefore is much smaller. The imported and desalinated water distribution systems have similar emissions because they use the same potable water distribution system.

Fig. 2 shows the graphical comparison of the GWP of the two utilities in units of carbon dioxide equivalents (CO_2 eq.) per functional unit. The comparison of GWP emissions by case study and water source mirrors the results for energy consumption. For the MMWD, desalination produces almost three times more GWP than recycled water and five times more than imported water. In the OWD system, desalination creates twice the GWP of recycling or importing water. Desalination in the MMWD has twice the GWP compared to the OWD because the salinity of the influent water is different as previously discussed. Recycling water is also twice as GWP intensive in the MMWD. For the two systems, the results for imported water are similar.

Fig. 2a highlights the contribution of each life-cycle phase to the final GWP results. Operation is consistently the dominant phase, followed by the maintenance phase. Operation comprises 60% to 91% of the total GWP result for all phases. The maintenance phase accounts for 5% to 36% of the total GWP. Construction causes 4% to 9% of the total results. Desalination system maintenance is higher than for the other sources (36% and 28% in the MMWD and the OWD systems, respectively) because the treatment process includes more components which must be replaced regularly (e.g., RO membranes, cartridge filters). The MMWD GWP contribution is larger because components from a seawater desalination system will be replaced more frequently that for a brackish water system due to additional wear caused by higher salinity. Maintenance of the MMWD imported water system is also relatively high (24%) because of the complex distribution system.



a) Global Warming Potential of Water Supply Alternatives by Life-cycle Phase

b) Global Warming Potential of Water Supply Alternatives by Water Supply Phase

c) Global Warming Potential of Water Supply Alternatives by Activity

Fig. 2: Global warming potential results

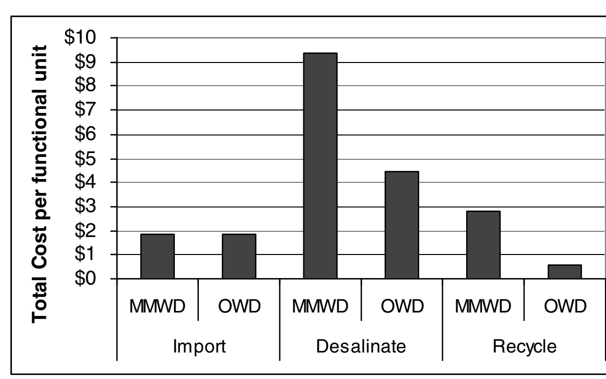
For imported water, the effects of construction and maintenance are smaller for the OWD due to economies of scale: the supply system provides water to the entire Southern California region so the effects are widely distributed. Recycled water results are also smaller for the construction and maintenance phases in the OWD case study but for a different reason. In this case, the OWD recycling system is simpler and requires fewer routine inputs such as chemicals. The OWD process only filters water; the MMWD system filters and disinfects.

Fig. 2b shows that treatment is not a significant contributor to the imported water system for either case, especially for the MMWD which uses a simpler treatment process. For both case studies, treatment contributes less than 5% to overall GWP. However, it is the largest contributor to the desalination emissions in both Marin County and Oceanside due to the energy intensity of RO systems. Treatment creates 83% of the MMWD's GWP and 88% of the OWD's GWP. The MMWD attributes 12% of its GWP to the distribution phase; the OWD only 5%. In addition to higher energy requirements for pumping, the MMWD system requires additional distribution infrastructure to be used solely for desalinated water but the OWD requires no additional piping.

Distribution is the largest GWP contributor to both recycled water systems accounting for 53% for the MMWD and 74% for the OWD. The recycling plants are located near the wastewater treatment plants which provide their water, minimizing the supply phase impacts. They have relatively simple treatment processes (i.e., filtration and disinfection at the MMWD [32% of emissions] and filtration only at the OWD [12% of emissions]). However, wastewater treatment plants tend to be located at lower elevations to minimize energy necessary to collect sewage; therefore, distributing recycled water tends to require significant pumping.

Fig. 2c provides the results as contributed by each of the four considered activities: material production, material delivery, equipment use, and energy production. In all cases, energy production is the largest contributing activity, comprising 56% to 69% of the total GWP. Material production is also a significant contributor and accounts for 30% to 44% of the result. Material production is most significant for desalination because the treatment process has more components requiring routine replacement. In all cases, material delivery and equipment use are negligible, contributing less that 0.6% to the overall emissions.

Fig. 3 shows median external cost estimates associated with the evaluated air emissions for each case. The majority of the external costs in all cases are caused by GWP (61–79% of total external costs), but NO_x and SO_x are also important contributors (7–16% each). For the OWD, the external costs associated with imported water are 8% of the production costs. Desalination external costs are 6% of water production costs for both case studies. External costs for the recycled water systems and for the MMWD imported water system are 1–2% of production costs. External costs are borne by society, but not paid by producers or reflected in typical agency accounting systems. These cost percentages suggest that to internalize the environmental externalities of these water supply options and introduce full-cost pricing, the price of water should be higher.



NOTE: The functional unit is equivalent to 123 million liters.

Fig. 3: Median estimate of external costs of air emissions from water Production

5 Uncertainty and Sensitivity

Sources for uncertainty in the used parameters include the service life of component parts, material costs, emission factors, and environmental valuation estimates. In addition, the results are affected by future events, including technological and efficiency improvements in the desalination process, and changes in the energy mix.

Sensitivity analyses were conducted to determine how variations in critical parameters would affect the results. In one analysis, the results were reevaluated after the service lives for all capital components were multiplied by 150%, reducing component replacement frequency. This sensitivity analysis was conducted using the MMWD system data. The increased service life reduced the effects of the construction and maintenance phases by between 7% and 82%. The effects in the construction phase were reduced by approximately 30% for all substances, supply phases, and sources, with the exception of desalination treatment. Desalination treatment emissions changed only 3% to 11% because the system is composed of fewer materials with long service lives (greater than 75 years). The maintenance phase reductions were more significant (62–82%) due to repeated purchases of certain components (e.g., pumps, valves, fittings). Desalination treatment is again the exception (1–8% reductions) for the previously mentioned reasons. The operation phase was unaffected because it almost exclusively includes materials which are consumed immediately (e.g., chemicals) and therefore are not assigned service lives.

The energy mix also affects the results. For example, using emission factors for Florida, another state where similar water sources are considered, will increase emissions caused by electricity production by a factor of 2 for GWP, 6 for NO_x, and more than 30 for SO_x. The energy mix is the sole reason for the difference. California's electricity mix consists primarily of natural gas (48.7%), nuclear power (18.6%), hydropower (16.8%), and renewables (12.9%) [44]. Coal, a fuel that typically produces higher emissions, comprises only 1.3% of production. Florida obtains 25.7% of electricity from coal plants and 43.8% from dual-fired plants (combination of coal, natural gas, and petroleum).

6 Conclusions

The results of this analysis indicate that the needs of the end-user should be evaluated in the planning process. Recycled water is more environmentally benign than desalination and should be pursued if customers can be found to use the non-potable water. Future analyses should evaluate the effects of putting separate piping systems in newly-constructed facilities so recycled water can be used for toilet-flushing, landscaping, and similar uses. This information would help attract and prioritize potential recycled water customers.

The results also show that the emphasis on desalination systems may not be the most sustainable decision as the environmental burden associated with these systems is significant. However, it is important to note that the assessment assumes the use of current desalination technology. Because the RO process is an emerging technology, the membranes can be expected to become more efficient as the technology improves. If the membranes become more durable and the RO process uses less energy, the environmental effects of desalination may decrease.

Energy efficiency may make brackish water desalination competitive with other water sources. For the OWD system, if energy consumption by the RO treatment process were reduced by 70%, desalinated and imported water would be equivalent in terms of GWP. However, for the MMWD system, energy consumption cannot be reduced enough in the operations phase to make desalination competitive with imported water; energy reductions would have to be made throughout the life-cycle, including the energy required to produce the membranes and other system components. Life-cycle energy consumption must be reduced by 75% for the MMWD system and 45% for the OWD system to achieve imported water GWP levels.

The results suggest that externalities due to life-cycle effects should be considered in future water supply decisions. The costs associated with externalities add 1–8% to the production costs of water. If other environmental effects (e.g., habitat loss due to withdrawing water) were evaluated, the significance of external costs would increase further. Because systems constructed today will be in place for decades, understanding the sources and effects of these externalities is critical.

6.1 Application to other water utilities

Results for similar water systems will be affected by site-specific issues including topography, process design, location, distance to water sources, climate, scale, and other factors. However, the OWD imported water supply results will be fairly consistent with other Southern California utilities that primarily use water from the Colorado River and the San Joaquin Delta. In fact, the Metropolitan Water District of Southern California sold almost 500 billion liters to the San Diego County Water Authority (SDCWA) in 1998, approximately 7% of that volume was sold to the OWD [37]. Taking the volume of water provided as typical, supplying water to this area without accounting for treatment and distribution consumes over 900,000 MWh, or 1.8% of California's 2002 net electricity generation [44]. If the OWD's treatment and distribution systems are typical of other Southern California utilities, treated water provision to the region consumes 2% of California's 2002 electricity generation.

Two factors contributed to the difficulties in data collection and potentially to data quality issues: security concerns that prevented full disclosure, and lack of data collection by utilities. Security concerns affected the detail of information about water systems. A more significant limitation was lack of data collection by utilities. In certain cases electricity consumption data were available only on a systemwide basis. Assumptions were necessary to allocate energy consumption among the components of the systems. For both case studies, detailed information on the recycled water system was not available and assumptions had to be made. More specific information would improve the quality of the results by reducing the uncertainty in the input data.

6.2 Future work

This assessment of the environmental effects of water systems will be improved and extended in the future. WEST will be refined to include other emissions and impact assessments. For example, emissions to water or land could be incorporated, and results could be evaluated to determine their human or ecosystem toxicity potential. The tool will be extended to assess alternative infrastructure choices (e.g., steel versus concrete water storage tanks, iron versus plastic pipe). Given that hundreds of billions of dollars will have to be spent on water system infrastructure in the next decades, the environmental effects of investments could be considerable and should be minimized.

Water supply decisions are made based on several criteria, including economic, political, social, and reliability concerns. Previously, the comprehensive and systemwide life-cycle environmental effects associated with the water infrastructure have not been a factor in these decisions. The model and WEST will allow utilities and other planners to incorporate these effects into their decision-making process and, with more informed analyses, strive for sustainable solutions.

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References

[1] USBR (2003): Water 2025 – Preventing Crises and Conflict in the West. US Bureau of Reclamation, Washington, DC
[2] California Assembly (1990): Urban Water Management Plan Act, California Assembly Bill 2661
[3] Stokes J (2004): Life Cycle Assessment of Alternative Water Supply Systems in California. Unpublished Ph.D. Dissertation. University of California, Berkeley
[4] ASE (2002): Watergy: Taking Advantage of Untapped Energy and Water Efficiency Opportunities in Municipal Water Systems. Alliance to Save Energy/ US Agency for International Development
[5] Herz R, Lipkow A (2002): Life Cycle Assessment of Water Mains and Sewers. Water Sci Technol: Water Supply 2 (4) 51–72
[6] EPA (2002): Clean Water and Drinking Water Infrastructure Gap Analysis. US Environmental Protection Agency
[7] Levine A, Asano T (2004): Recovering Sustainable Water from Wastewater. Environ Sci Technol 38 (11) 201A–208A
[8] Lundie S, Peters, GM, Beavis PC (2004): Life Cycle Assessment of Sustainable Metropolitan Water Systems Planning. Environ Sci Technol 38 (13) 3465–3473
[9] Raluy, RG, Serra L, Uche J (2004): Life Cycle Assessment of Water Production Technologies Part 1. Int J LCA OnlineFirst, September 29 <DOI: http://dx.doi.org/10.1065/lca2004.09.179.1>
[10] Raluy RG, Serra L, Uche J, Valero A (2004): Life Cycle Assessment of Water Production Technologies Part 2. Int J LCA OnlineFirst, September 29 <DOI: http://dx.doi.org/10.1065/lca2004.09.179.2>
[11] Rogers P (2004): Valley Firms to Fight Global Warming. The Mercury News, San Jose, March 29
[12] van Tilburg J, Nieuwlaar E, Geerts, J (1997): Environmental Analysis for Choosing between a Single or Double Domestic Water Supply. 5th LCA Case Studies Symposium, SETAC Europe: Brussels, Belgium, pp 213–220
[13] Crettaz P, Jolliet O, Cuanillon JM, Orlando S (1999): Life Cycle Assessment for Drinking Water and Rain Water for Toilets Flushing. Aqua 48 (3) 78–83
[14] Friedrich E (2002): Life Cycle Assessment as an Environmental Management Tool in the Production of Potable Water. Water Sci Technol 46 (9) 29–36
[15] Filion Y (2003): New York City Primary Water Supply System: Net Energy Expenditure Analysis of Long-term Management Strategies. University of Toronto, Department of Civil and Environmental Engineering, Technical Report
[16] Hermanowicz S, Diaz E, Coe J (2001): Prospects, Problems, and Pitfalls of Urban Water Reuse: A Case Study. Water Sci Technol 43 (10) 9–16
[17] Das T (2002): Evaluating the Life-cycle Environmental Performance of Chlorine Disinfection and Ultraviolet Technologies. Clean Technologies and Environmental Policies 4, 32–43
[18] Curran MA (ed) (1996): Environmental Life Cycle Assessment. McGraw-Hill, New York
[19] CMU (2004): Economic Input-Output LCA. Carnegie Mellon University, Green Design Initiitive. <http://www.eiolca.net> (Accessed March 2004)
[20] SETAC (1991): A Technical Framework for Life Cycle Assessment. Society of Environmental Toxicology and Chemistry Workshop Report: Smugglers Notch, Vermont
[21] SETAC (1993): Guidelines for Life Cycle Assessment: A Code of Practice. Society of Environmental Toxicology and Chemistry, Sesimbra, Portugal
[22] Vigon BW (1993): Life Cycle Assessment: Inventory Guidelines and Principles. US Environmental Protection Agency, Cincinnati, Ohio
[23] ISO (1997): Environmental Management – Life Cycle Assessment – General Principles and Framework. International Organization for Standardization
[24] ISO (1998): Environmental Management – Life Cycle Assessment – Goal and Scope Definition – Inventory Analysis. International Organization for Standardization
[25] ISO (2004): ISO 14000. International Organization for Standardization. <http://www.iso.ch/iso/en/iso9000-14000/iso14000/iso14000index.html> (Accessed March 2004)
[26] Graedel TE, Allenby BR (2003): Industrial Ecology; 2nd ed. Prentice Hall, Upper Saddle River, NJ
[27] Hendrickson C, Horvath A, Joshi S, Lave L (1998): Economic Input-Output Models for Environmental Life Cycle Assessment. Environ Sci Technol 32 (4) 184A
[28] Toffel MW, Horvath A (2004): Environmental Implications of Wireless Technologies: News Delivery and Business Meetings. Environ Sci Technol 38 (11) 2961–2970
[29] Pacca S, Horvath A (2002): Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin. Environ Sci Technol 36 (14) 3194–3200
[30] Okun DA (1997): Distributing Reclaimed Water through Dual Systems. J AWWA 89 (11) 13
[31] Matthews HS, Hendrickson C, Horvath A (2001): Applications of Environmental Valuation for Determining Externality Costs. J of Infrastructure Sys 7 (1) 111–117
[32] MMWD (1990): Why Desalination May be Our Best Water Supply Option. Marin Municipal Water District
[33] MMWD (1995): Urban Water Management Plan. Marin Municipal Water District
[34] MMWD (2003): Draft Urban Water Management Plan 2000. Marin Municipal Water District
[35] MWD (1996): Integrated Water Resources Plan. Metropolitan Water District of Southern California
[36] MWD (2000): Regional Urban Water Management Plan. Metropolitan Water District of Southern California
[37] SDCWA (2000): Urban Water Management Plan. San Diego County Water Authority
[38] OWD (2001): Urban Water Management Plan. City of Oceanside Water Utilities Department
[39] Means RS (1997): Heavy Construction Cost Data, 12th ed. Kingston, MA
[40] Mays L (1999): American Water Works Association. Water Distribution Systems Handbook. McGraw-Hill, New York
[41] American Society of Civil Engineers, American Water Works Association (1998): Water Treatment Plant Design 3rd ed. McGraw-Hill: New York
[42] Nayyar M (2002): Piping Databook. McGraw-Hill, New York
[43] Peters M, Timmerhaus K, West R (2003): Plant Design and Economics for Chemical Engineers 5th ed. McGraw-Hill, New York
[44] DOE (2004): State Electricity Profiles. US Department of Energy, Energy Information Administration. <http://www.eia.doe.gov/cneaf/electricity/st_profiles/toc.html> (Accessed July 8, 2004)

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